

# **An approach for Averaging Surface Temperature and Surface Fluxes over Heterogeneous Terrain**

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## **Abstract**

Successful prediction of possible climate change depends on realistic parameterizations of land-surface processes in climate models. Such parameterizations must take into account, in an appropriate manner, the surface heterogeneities that are found in the real world. In this study, different averaging strategies for aggregating small scale heterogeneities to scales which are appropriate for mesoscale and climate model grids were explored. A simple model for estimating area-average "effective" controlling parameters is suggested. The model is based on the assumption that effective emissivity can be described as a simple areal average of the individual emissivities of the elements of the surface. This leads to a set of relationships between local and effective parameters in the governing equations for the surface energy balance. The results show that the effective surface temperature is not a simple areal average of component temperatures, but is a function of a specific combination of different resistances of the individual surface elements. A set of heterogeneous surfaces has been simulated, and effective parameters and effective fluxes have been obtained using the described model. A comparative study with results obtained using other averaging models is also performed.

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## 1. Introduction

It has been increasingly apparent in recent years that understanding the partitioning of available radiative energy at the land surface into sensible and latent heat fluxes, is a critical issue in modeling and predicting climate change both on global and regional scales. A number of numerical simulations have shown that the partitioning of available energy at the surface is the dominant factor in producing and modifying the mesoscale atmospheric circulations (Avisar and Pielke, 1989). Therefore, it is reasonable to conclude that successful simulation of climate variability depends on a realistic representation of the land-surface energy and mass balance (Koster and Suarez, 1992).

Several land-surface models (multi-layer models) for global and mesoscale predictions have been developed during the last decade ( Dickinson et al., 1986; Sellers et al., 1986; Taconet et al., 1986). These models generally resolve explicitly in several layers the vertical structure of the soil, vegetation canopy and atmospheric surface layer, and a large number of input parameters are required. In contrast, the single layer based models required only a few input parameters and can produce a good estimates of surface fluxes, when they are well calibrated over a specific site.

The main difficulties encountered in reliable prediction of surface fluxes concern two aspects. The first, is that certain biological and aerodynamic processes, such as the stomata control on transpiration rate and estimation of the turbulent wind field in the leaf boundary layer, are quite complex and they are often handled in crude manner (McNaughton, 1987). The second aspect is related to the fact that the commonly used

homogeneous surface parameterizations, based on boundary-layer similarity theory, are inappropriate to represent the subgrid spatial variability that is found in the real world.

Recent numerical studies (Mahfouf et al., 1987) have shown that sea-breeze-type mesoscale circulations develop along the discontinuity between the bare soil and vegetated surfaces, contributing to enhance convective cloud development. Segal et al. (1989) and Hetchel et al. (1990) dispute that surface heterogeneities of temperature critically impact the behavior of boundary layer circulations. It is thus important, to incorporate realistically subgrid spatial variability in boundary-layer schemes that are used to model mesoscale atmospheric systems.

Several approaches that attempt to better represent the fluxes associated with heterogeneous surfaces have been recently reported in the literature. The concept of the so-called "blending height" has become a leading approach for practical averaging flux of heat and momentum over heterogeneous surfaces (Claussen, 1991). This concept was defined by Wieringa (1986) as the height at which the flow emanating from each element of the grid becomes independent of its horizontal position. This is particularly suitable for large-scale regions containing multiple, spatially distinct micro-climate regimes. But it may have some difficulty representing regions where the components of the grid interact strongly. Shuttleworth (1993), Koster and Suarez (1992), and Raupach (1991), reported that for a surface with disorganized variability (the scale of the heterogeneities is smaller than the integral mixing scale), a proper representation of sub-grid variability could be to assume that different element of the grid are acting in parallel, which suggests that the equivalent resistance over the entire grid can be obtained as the area-weighted parallel sum of all the resistance values for the individual elements of the grid. This approach was applied with success to estimate sensible heat flux over heterogeneous terrain during the Hapex Sahel Experiment (Chehbouni et al., 1993). Recently Lhomme

(1992), assuming that the effective temperature of the entire grid is a simple areal average of the temperatures of the individual elements, has shown that the resulting effective controlling parameters (such as resistances and albedo) are then expressed as weighted means of the parameters specific to each element of the grid. The weighting coefficients are functions of the relative area and a combination of the resistances of each element. However, assuming that the effective surface temperature is a simple areal average of the temperatures of individual elements of the surface “we have termed this simple average the composite temperature” is not justifiable in regions where strong contrasts between individual elements of the grid exist (arid and semi-arid regions). Data collected during the Monsoon 90 experiment (Kustas et al., 1991) have shown that the difference between the composite temperature (defined above) and the radiative temperature obtained from outgoing long wave radiation can reach 8 degrees (C). Such differences which can lead to large errors in surface flux estimation. As reported by Seguin (1993), a precision of 2 degrees (C) in surface temperature corresponds to a precision of approximately 20 to 60 W/m<sup>2</sup> in sensible heat flux (depending upon the aerodynamic values used),

In this study, a basic one layer energy balance model has been used, with a different approach for obtaining controlling parameters for the surface fluxes in which it is assumed that the effective emissivity for heterogeneous surface can be represented by an areal average of individual emissivities of the surface components. This assumption is more justifiable than that taken by Lhomme (1992) since the emissivities of major natural surfaces in the thermal infrared spectral band are fairly uniform and range within a few percent only (between 0.95 and 0.99) (see Labed and Stoll, 1991). Also, the surface emissivity is often assumed constant over all grid elements in current mesoscale models.

The model for estimating effective controlling parameters is presented in the first part of the paper. In the following section, the approach is validated using a large set of simulated data representing different heterogeneous surfaces. In the last part of the paper, the results obtained with this averaging strategy are compared with those obtained using other averaging strategies.

## 2. Modeling approach

In this analysis, we assume that the horizontal fluxes between different elements of the grid are small compared to the vertical fluxes. We also assume that the atmospheric forcing factors are similar for all elements of the grid (incoming short and long wave radiation, air temperature, air vapor pressure, wind speed). A basic one layer model is used to estimate different term in the energy balance equation for each element of the grid.

$$R_n = G + LE + H \quad (1)$$

where  $R_n$  is net radiation,  $G$  is soil heat flux,  $H$  and  $LE$  respectively represent sensible and latent heat flux. These term are expressed as:

$$H = \rho C_p \frac{T_s - T_a}{r_a} \quad (2)$$

$$LE = (\rho C_p / \gamma) \frac{e^*(T_s) - e_a}{r_a + r_s} \quad (3)$$

$$R_n = (1 - \alpha) R_s + \varepsilon (R_l - \sigma T_s^4) \quad (4)$$

where  $p$  is the mean air density,  $C_p$  is the specific heat of air at constant pressure,  $\gamma$  is the psychrometric constant,  $T_a$  and  $e_a$  are the temperature and the vapor pressure of the air at a reference height,  $e^*(T_s)$  is the saturated vapor pressure at temperature  $T_s$ ,  $R_s$  and  $R_l$  are respectively the incoming short and long wave radiation,  $\alpha$  and  $\epsilon$  are the surface albedo and emissivity,  $r_a$  and  $r_s$  are respectively aerodynamic and surface resistance to transfer from the surface to the well mixed layer. Many authors have reported (see Brustear, 1982) that in natural surfaces, it is legitimate to linearize surface saturated vapor pressure and surface temperature as:

$$e^*(T_s) - e_a = s (T_s - T_a) + D_a \quad (5)$$

$$T_s^4 = T_a^4 + 4T_a^3 (T_s - T_a) \quad (6)$$

where  $s$  is the slope of the saturated vapor pressure curve at air temperature, and  $D_a$  is the vapor pressure deficit in the air.

Following an approach similar to that used in Lhomme (1992), we substitute Equations (2) through (6), into the energy balance Equation (1) to obtain:

$$(\rho C_p / w) [(T_s - T_a) + w D_a / (\gamma (r_a + r_s))] = [(1 - \alpha) R_s + \epsilon (R_l - \sigma T_a^4) - G] \quad (7)$$

where  $w$  is defined as :

$$1/w = 1/r_o + 1/r_a + s / (\gamma (r_a + r_s)) \quad (8)$$

and  $r_o$  is the resistance to radiative transfer, defined by Monteith (1973) as :

$$r_o = (\rho C_p / 4 \varepsilon \sigma T_a^3) \quad (9)$$

Equation (7) can be rewritten in the following manner :

$$\varepsilon = [(\rho C_p / w) (T_{si} - T_a) + (\rho C_p / \gamma) D_a / (r_a + r_s) + G - (1 - \alpha) R_s] / RL \quad (10)$$

$$\text{where } RL \text{ is defined as : } RL = R_l \cdot 0.7 \cdot a^4 \quad (11)$$

Following Lhomme ( 1992), Equation ( 10) can be written for each individual element (i) of this grid as :

$$\varepsilon_i = [(\rho C_p / w_i) (T_{si} - T_a) + (\rho C_p / \gamma) D_a / (r_{ai} + r_s) + G_i - (1 - \alpha_i) R_s] / RL \quad (12)$$

By assuming that the effective surface emissivity can be expressed as a simple areal average of the individual surface elements (Eq. 13), effective surface emissivity can be rewritten as :

$$\varepsilon = \sum a_i \varepsilon_i \quad (13)$$

$$\varepsilon = [\rho C_p \sum (a_i / w_i) (T_{si} - T_a) + (\rho C_p / \gamma) D_a \sum (a_i / (r_a + r_s)) + \sum a_i (G_i - (1 - \alpha_i) R_s)] / RL \quad (14)$$

where  $a_i$  denotes the fraction cover of the element i of the surface defined such as :

$$\sum a_i = 1$$

Matching Equations (10) and (14) leads to the following relationships:

$$Ts = w \sum (a_i T_{si} / w_i) \quad (15)$$

$$1 / w = \sum a_i / w_i \quad (16)$$

$$1 / (r_a + r_s) = \sum a_i / (r_{ai} + r_{si}) \quad (17)$$

$$G = \sum a_i G_i \quad (18)$$

$$\alpha = \sum a_i \alpha_i \quad (19)$$

On the other hand, by combining Equations (8), (9) and (16), the following expressions can be inferred:

$$1 / r_o = (\sum a_i \epsilon_i) 4 \sigma T_a^3 / \rho C_p = \epsilon 4 \sigma T_a^3 / \rho C_p \quad (20)$$

$$1 / r_a = \sum a_i / r_{ai} \quad (21)$$

At this point, given the assumed hypothesis, we can summarize the relationship between local and effective controlling factors as:

1 ) The surface temperature is not a simple areal average of the component temperatures, but also depends on a given combination of the individual component resistances.

2) The effective aerodynamic resistance,  $r_a$ , is the area-weighted parallel sum of all the  $r_{ai}$  values of the individual elements.

3) The effective sum of the aerodynamic and surface resistances,  $(r_a + r_s)$ , is also the area-weighted parallel sum of all the  $(r_{ai} + r_{si})$  values of the individual elements.

4) the equivalent surface albedo as well as the equivalent soil heat flux are a simple area] average of the values of each element of the grid.



These last three relations, which are here derived analytically from the energy balance equation, (as in Raupach, 1991) are similar to the ones suggested in the literature by assuming an Ohm's law analogy (Koster and Suarez, 1992; Shuttleworth, 1993). However, the expression of effective surface temperature is different from the commonly used expression which assumes that the effective surface temperature is equal to "composite" the simple areal average temperature (i. e.,  $T_c = \sum a_i T_{si}$ ).

The difference between composite ( $T_c$ ) and effective surface temperature ( $T_s$ ) for an heterogeneous area formed by  $n$  elements can be expressed as:

$$T_c - T_s = \sum (a_i T_{si} / w_i) (w_i - w) \quad (22)$$

This equation shows that the difference can be either positive or negative, which means that by using the composite surface temperature to estimate surface fluxes over heterogeneous surfaces, the fluxes could be either over or under-estimated. Equation (22), if applied to a surface represented by two components, for example vegetation (covering an area  $a_1$ , and having, a temperature  $T_1$  and a coefficient  $w_1$ ) and soil ( $a_2$ ,  $w_2$ ), where  $1 - a_1 = a_2$ , leads to:

$$T_c - T_s = \frac{a_1(1 - a_1)}{a_1 w_2 + (1 - a_1) w_1} (T_2 - T_1) (w_2 - w_1) \quad (23)$$

According to this equation,  $T_c - T_s$  is positive if the differences ( $w_2 - w_1$ ) and ( $T_2 - T_1$ ) are both positive or both negative. The magnitude of the difference between the two temperatures is a function of the contrast of the actual characteristics (temperatures and resistances) of the elements of the surface.

### 3. Data used

Many natural surfaces can be represented at typical model grid scales as a mixture of two components. For this study, data set representing surfaces made up of mixtures of two components was synthesized. Each surface was represented by a given combination of two of the following elements: trees, shrubs, grass, agricultural crops, bare soil and open water. The relative area covered by each element was varied from 20 to 80 %. The emissivity values used in this study ranged from 0.99 for vegetation to 0.95 for bare soil. The overhead climatic parameters wind speed, air temperature, vapor pressure and incoming short-wave radiation, were assumed to be constant within the surface (grid square). In summary, 25 different heterogeneous surfaces were simulated. The input parameters for each surface is presented in Table 1. The purpose of this compositing is to simulate a surface with maximum contrast between individual elements, which is generally the case in the real world.

#### **4. Results and discussion**

To analyze the results using our approach, we have assumed that total sensible and latent heat fluxes exchanged between a given heterogeneous surface and the atmosphere are represented by a real average of the fluxes emanating from each element of the surface. Such fluxes are taken as reference and will be called the "true" fluxes. Before going into the comparisons between simulated and true fluxes, we will first present a direct comparison between composite surface temperature (simple areal average) and effective surface temperature obtained using our strategy (Equation 15). In figure 1, the difference between composite and effective surface temperature is presented for the 25 different surfaces. As stated in a previous section, one can see that this difference can be positive or negative. It varies from -3 to + 3.5 degrees C for the cases examined. The maximum difference generally occurs when the fraction covered by

each element of the surface ranges from about 40% to 60 %. The sign as well as the magnitude of the difference may change depending on the input parameters. For example, Figure 2 presents the difference between composite and effective surface temperature (for the surface represented in case 3) obtained using two different values of wind speed (respectively 1 and 4 m/s). Similar variations may be obtained by changing other input parameters. However, this pattern is likely to be more pronounced when parameters used to estimate aerodynamic resistance are varied, since the weighting factor  $w$  increases more rapidly with  $r_a$  than with  $r_s$  (Lhomme (1992)).

A comparison between simulated and true sensible heat flux is presented in Figure 3. It can be seen that the model reproduces accurately the true sensible heat flux. The model slightly over-estimates sensible heat flux in some cases, but not significantly. Figure 4 shows the same comparison for latent heat flux. In this case the model almost represents perfectly the true latent heat flux, the correlation coefficient is about 0.99. The numerical simulations clearly show how accurately sensible and latent heat flux can be retrieved using these simple aggregation rules. However, further validation with real data is needed before one can draw any final conclusions.

In the coming section, the model results will be compared to those obtained with other models. In the Lhomme (1992) model, the relationships between local and effective controlling parameters were obtained by assuming that surface temperature for a large grid is obtained by a simple areal average of the temperature of the individual elements of the grid. This leads to a set of aggregation rules which are quite different from those obtained here. The aggregation rules suggested by Shuttleworth (1993), Raupach (1991) and Koster and Suarez (1992) are similar to the ones obtained by our model, the only difference is in the expression of the effective surface temperature.

Effective latent and sensible heat fluxes for the 25 different surfaces were computed using the three models, ( I ) the present model (Ch); Lhomme (Lh) and Raupach model (Rh); (Raupach, 1991, Shuttleworth, 1993 and Koster and Soares, 1992, models are similar, but for simplicity purposes, we choose arbitrarily to refer to them as Raupach model). We then compute the corresponding percent error, defined as :  $((F_m - F_s)/F_s) * 100$ , where  $F_m$  (respect.  $F_s$ ) represents true flux (respect. simulated flux). Figure 5, shows a comparison between the three models for sensible heat flux percent error as a function of percent element cover. This figure shows that the Raupach model can overestimate sensible heat flux with an error up to 90 % (case 2). The Lhomme model reproduce sensible heat flux with about 65 % accuracy, except for case 5 where sensible heat flux is underestimated by almost 72 %. In contrast to those models, the estimation of sensible heat flux using the current model is more accurate, the percent error varies within +/-10%. Figure 6 presents the same comparison for latent heat flux. In general the Lhomme and Raupach models perform in similar manner, except for case 5, Lhomme's model underestimates latent heat flux about 50 % when the underestimation observed with Raupach model is about 25 %.

To summarize the performance of each of the three models, we have computed, for each surface type (5 cases, see "Table 1"), the average of the absolute value of the percent error with respect to the area cover. Figure 7 shows the corresponding percent error of the models in obtaining sensible (Figure 8 shows the same, but for latent heat flux). For both latent and sensible heat flux estimation, the Lhomme and Raupach models perform in very similar manner. The average percent error is about 40 % for sensible heat flux and about 30 % for latent heat flux, while those corresponding to the current model are below 10 %.

A simultaneous examination of Figure 1, 4 and 5 shows that for the Raupach model, a positive difference between composite and effective surface temperature leads to an overestimation of both sensible and latent heat flux, and vice versa.

A cross plot between the percent error in estimating surface fluxes versus the percent error in surface temperature (percent difference between composite and effective surface temperature) using the Raupach model is presented in Figure 9. This figure shows that the error in estimation surface fluxes is linearly correlated to the error in estimation effective temperature; the  $R^2$  is respectively about 0.90 and 0.97 for sensible and latent heat flux. The slope of the regression line for sensible heat flux is about double that for latent heat flux. An error of 10 % in the estimation of surface temperature can lead to an error 70 % in the estimation of sensible heat flux and about 35 % in the estimation of latent heat flux.

In summary, the aggregation scheme presented in this study appears to be successful in defining the effective, area average values of the key parameters that control surface atmosphere exchanges. The percent error in estimating latent and sensible heat flux was below 10 % for the 25 simulations. The major purpose of this study has been to define an original rule for aggregating surface temperature, which represents one of the most important key factors in surface-atmosphere mass and heat transfer. Surface temperature controls directly or indirectly all the energy balance components.

## 5. Conclusion

A numerical simulation has been carried out to assess different strategies of aggregating the controlling parameters of surface-atmosphere exchanges. This was performed for a large set of different heterogeneous surfaces (25). A new strategy based on the assumption that surface emissivity can be estimated by a simple areal average of individual emissivities of the components of the surface has been suggested. The relationship between local and effective controlling parameters are :

1 ) effective surface temperature is not a simple areal average of component temperatures, but it was also function of a given combination of different resistances of the individual elements of the surface.

2) effective aerodynamic resistance is obtained as area-weighted parallel sum of all resistances of individual elements.

3) effective albedo (respect. effective soil heat flux) is obtained from a simple areal average of albedo (respect. soil heat flux) of individual elements of the surface.

4) effective sum of aerodynamic and surface resistances is obtained as area-weighted parallel sum of all sum of aerodynamic and surface resistances of individual elements.

The simulation results show that with the suggested scheme the accuracy of obtaining sensible and latent heat flux was about 90 % , while the whose of other models was about 60 to 70%. However, those results should be balanced by the fact that only simulated data has been used to validate this strategy, but the validation with real data from Ilapex-Sahel Experiment are our next step.

The proposed aggregation rules are strictly valid only in the case of overhead climatic conditions are constant over the grid square, which means that the characteristics of the air in the well-mixed layer are assumed to be horizontally

homogeneous. Therefore, this scheme is plausible in the case where the scale of heterogeneities of the surface are smaller than the integrated mixing scale.

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Table 1: Summary of surface type and conditions used in our simulations

Case/Surface	$T_a$	$T_1$	$T_2$	%Cover	$U_a$	$r_{s1}$	$r_{s2}$	$r_{a1}$	$r_{a2}$	$E_a$
1: Grass-Forest	30	45	35	20-80	3	800	100	$223/U_a$	$50/U_a$	15
2: Crop-Forest	28	42	30	“ “	4	500	100	$223/U_a$	$50/U_a$	15
3 Water-Dry Soil	30	32	60	“ “	1,	0	500	$650/U_a$	$430/U_a$	10
4: Shrubs-Crop	30	55	35	“ “	2	500	300	$150/U_a$	$232/U_a$	12
5: Water-Forest	28	30	35	“ “	.8	0	500	$650/U_a$	$50/U_a$	25

Where,  $U_a$  is the wind speed (m/s),  $T_a$  is the air temperature (C),  $E_a$  is the air vapor pressure (Pa),  $T_i$  (  $i$  denote 1 and 2) is the temperature of the element  $i$  of the grid (C),  $r_{a1}$  and  $r_{s1}$  are respectively, aerodynamic and surface resistance of the element  $i$  of the grid (s/m) .

## Figure captions

Figure 1 : Difference between effective and composite surface temperature

Figure 2: Difference between effective and composite surface temperature for two values of wind speed (case 3).

Figure 3 : Comparison between simulated and **true** sensible heat flux.

Figure 4: Comparison between simulated and true Latent heat flux

**Figure 5:** Comparison between the accuracy of the 3 models in the estimation of sensible heat flux.

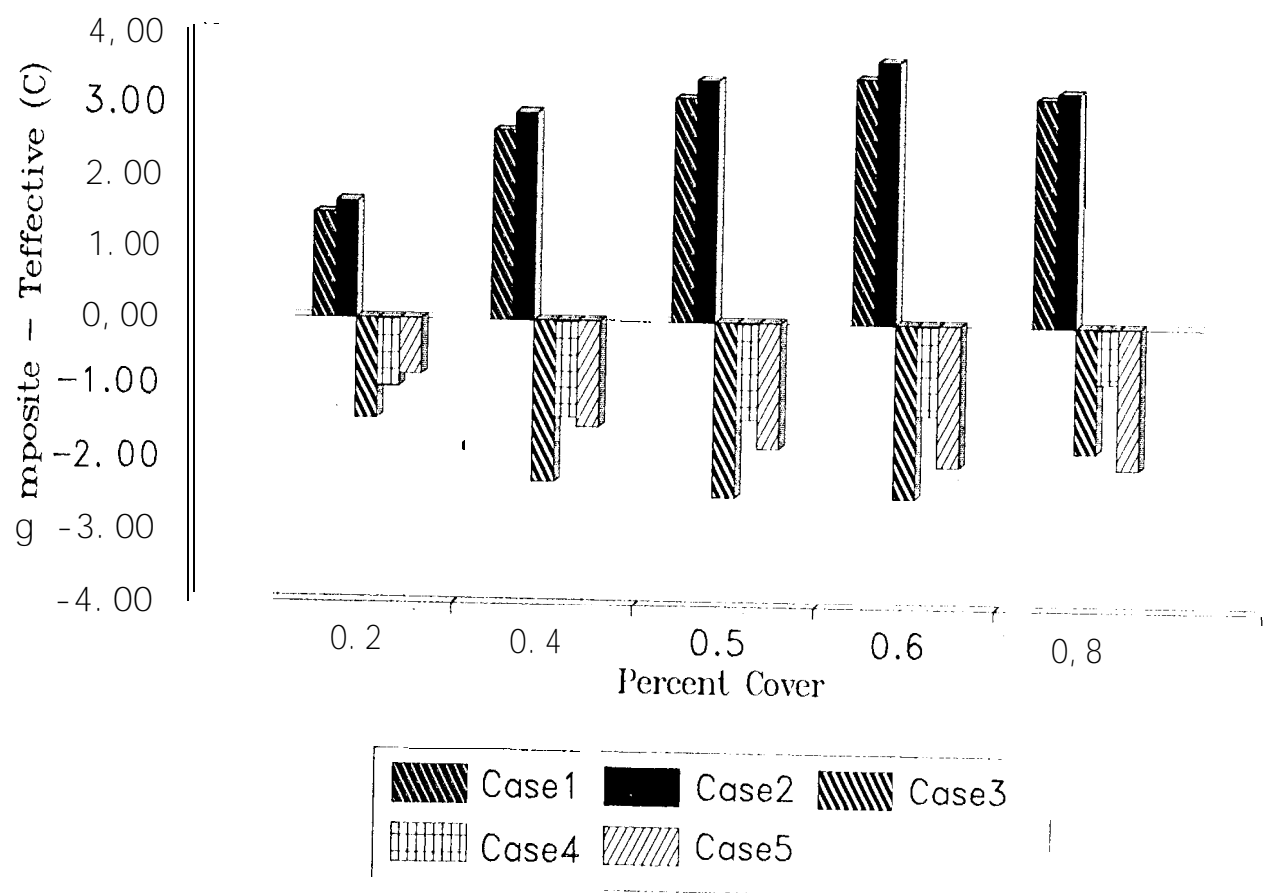
Figure 6: Comparison between the accuracy of the 3 models in the estimation of latent heat flux.

Figure 7: Comparison of the average accuracy of the 3 models in the estimation of sensible heat flux for each surface types.

Figure 8: Comparison of the average the accuracy of the 3 models in the estimation of latent heat flux for each surface types.

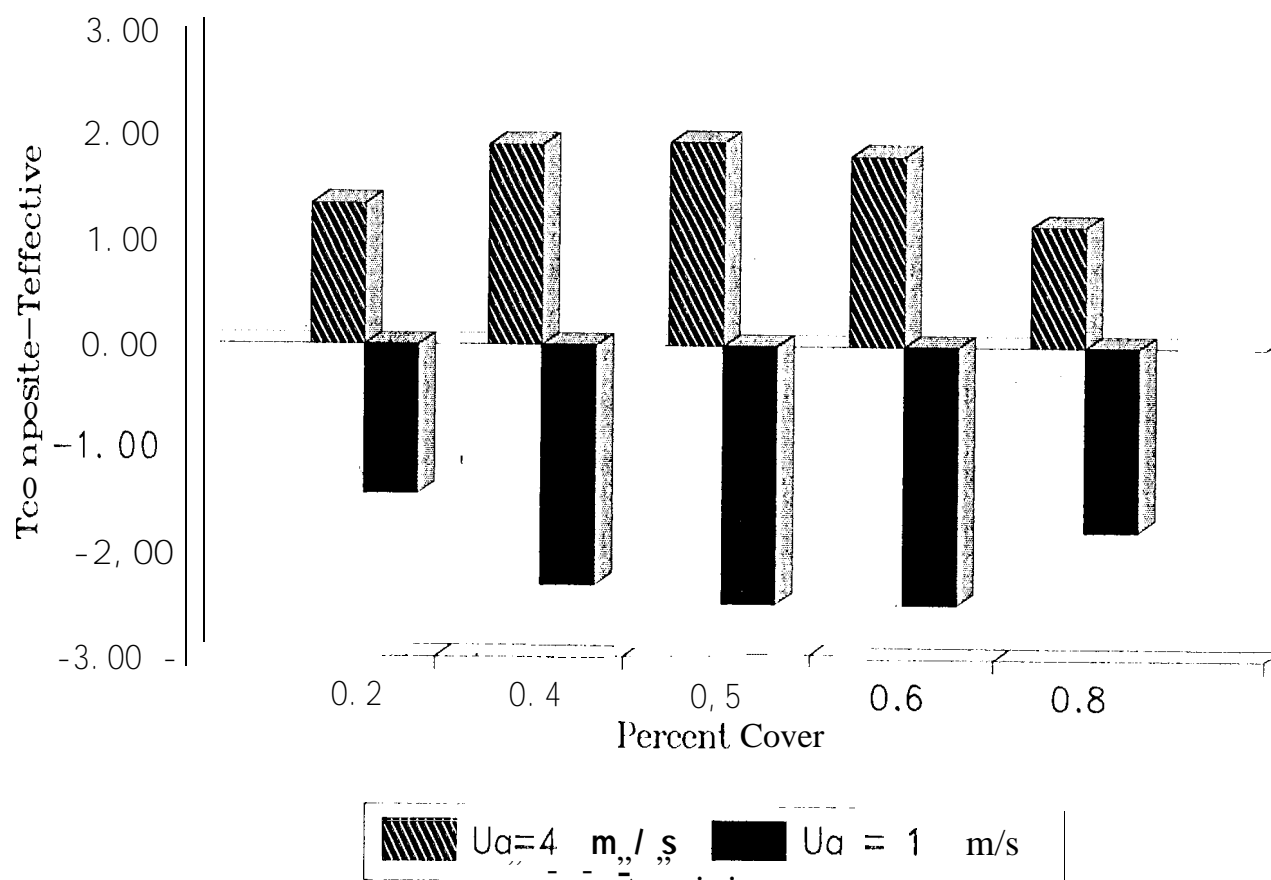
Figure 9: Cross plot between error in estimating surface temperature versus the error in estimating sensible and latent heat flux in the case of Raupach Model.

MODEL SIMULATION  
Surface temperature

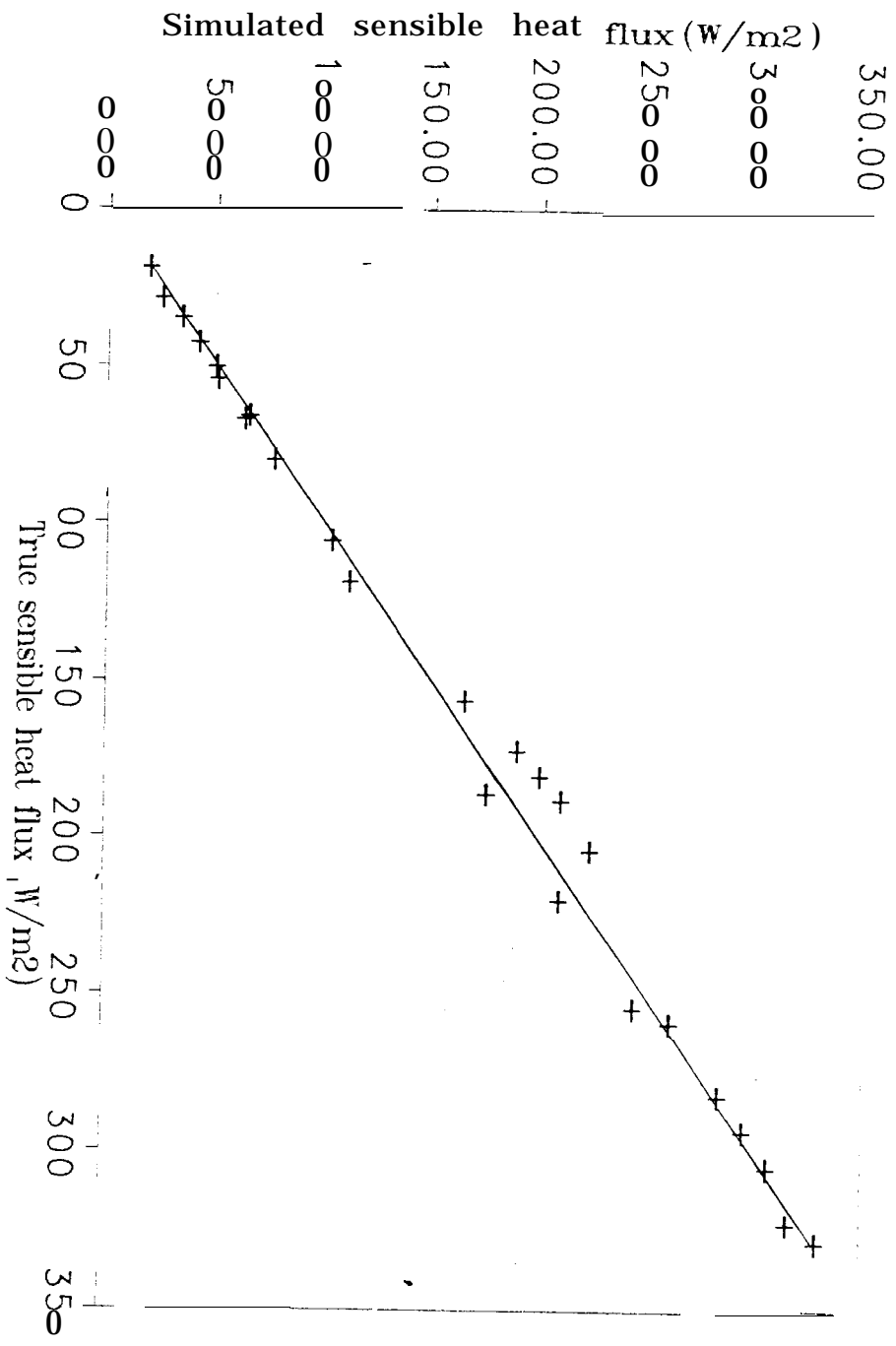


# SENSITIVITY ANALYSIS

Temperature difference

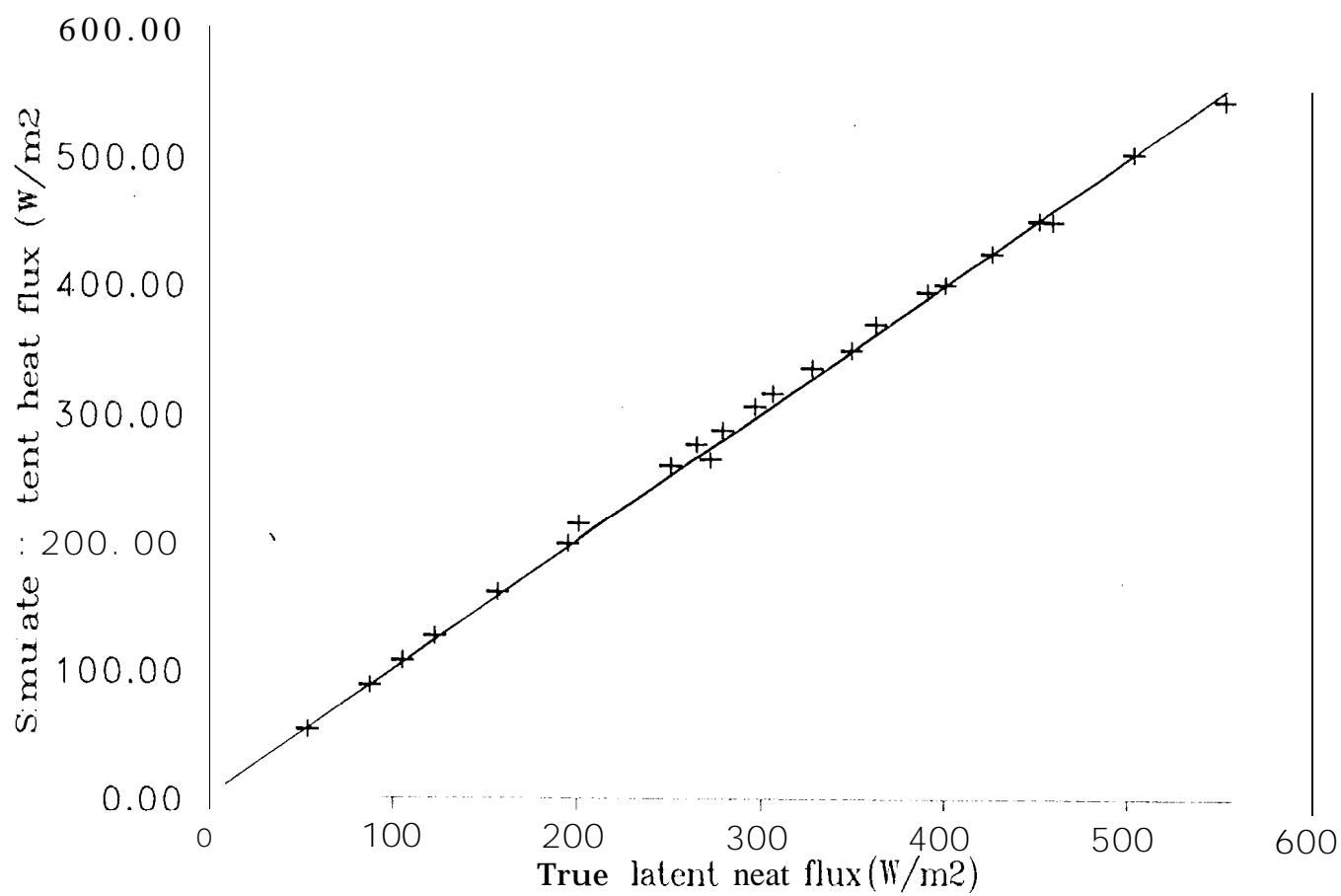


# MODEL VALIDATION Sensible Heat Flux



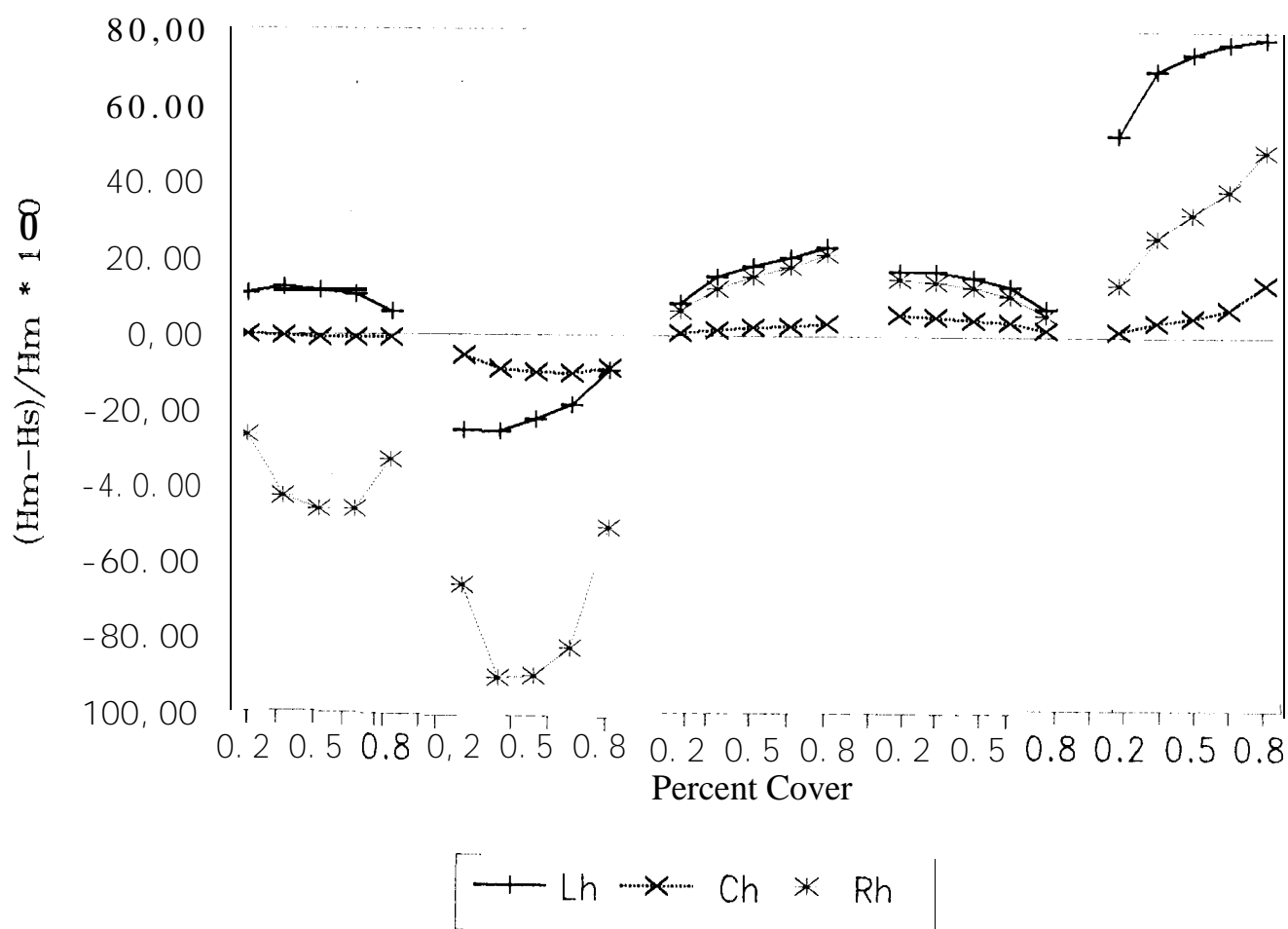
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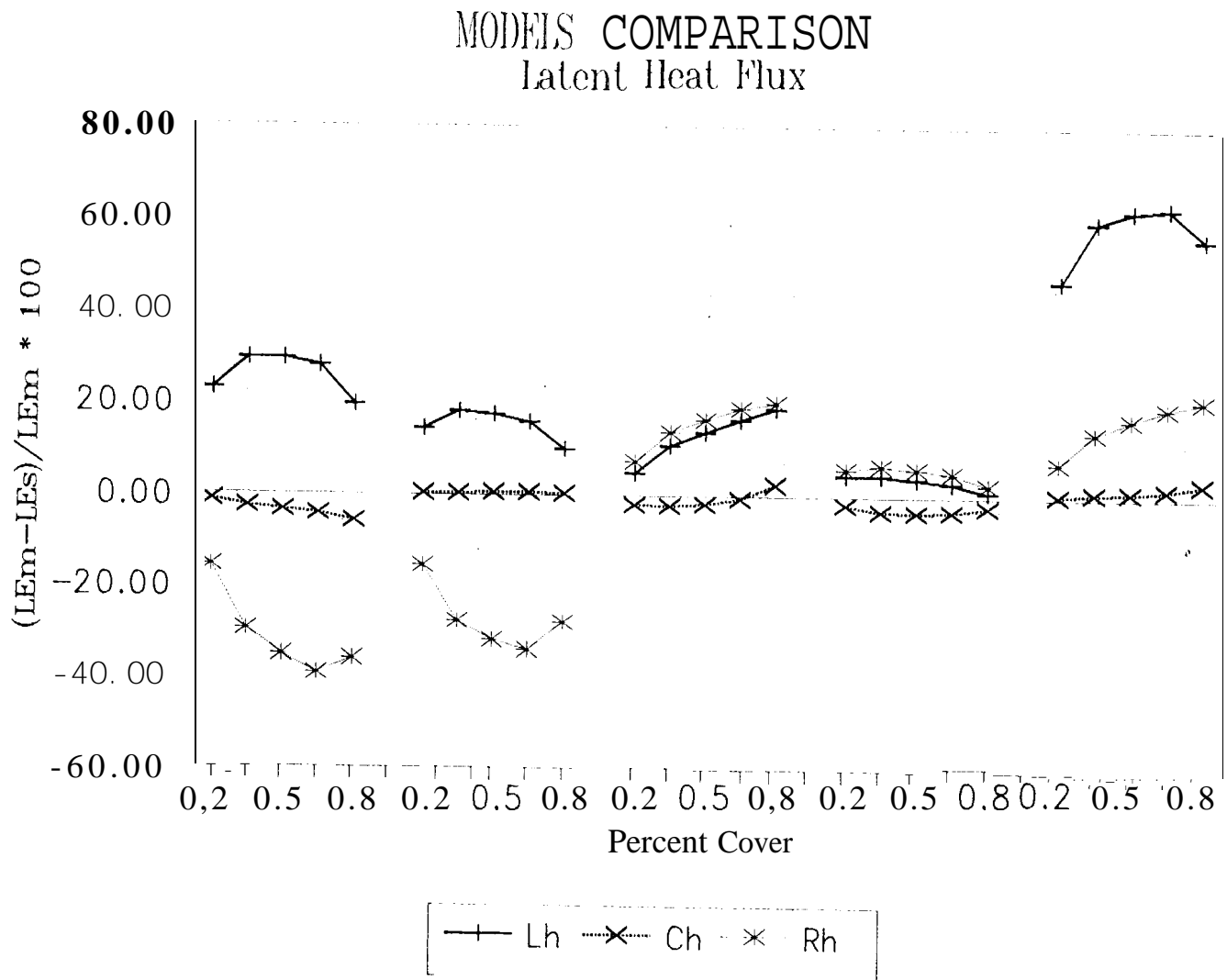
## Latent heat Flux



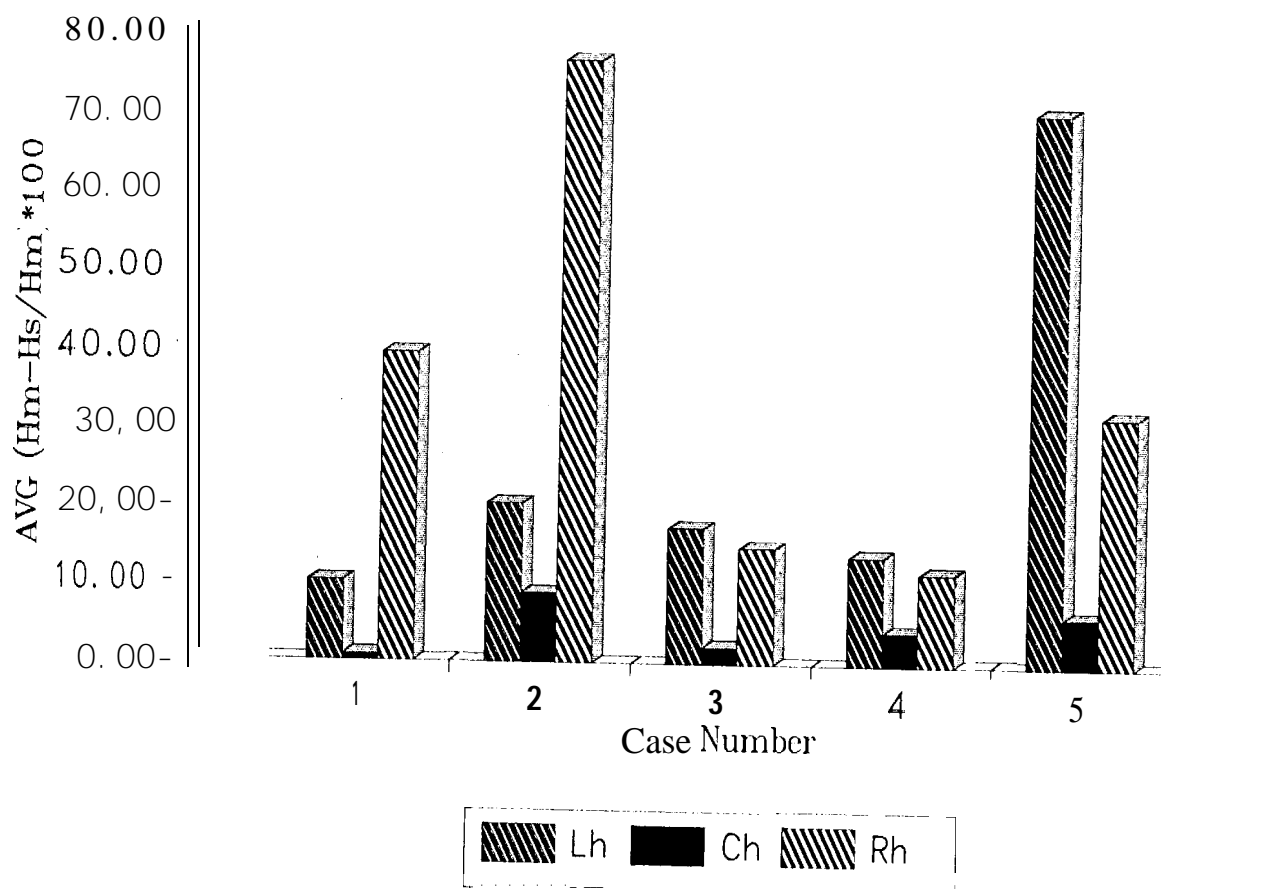


# MODELS COMPARISON Sensible Heat Flux



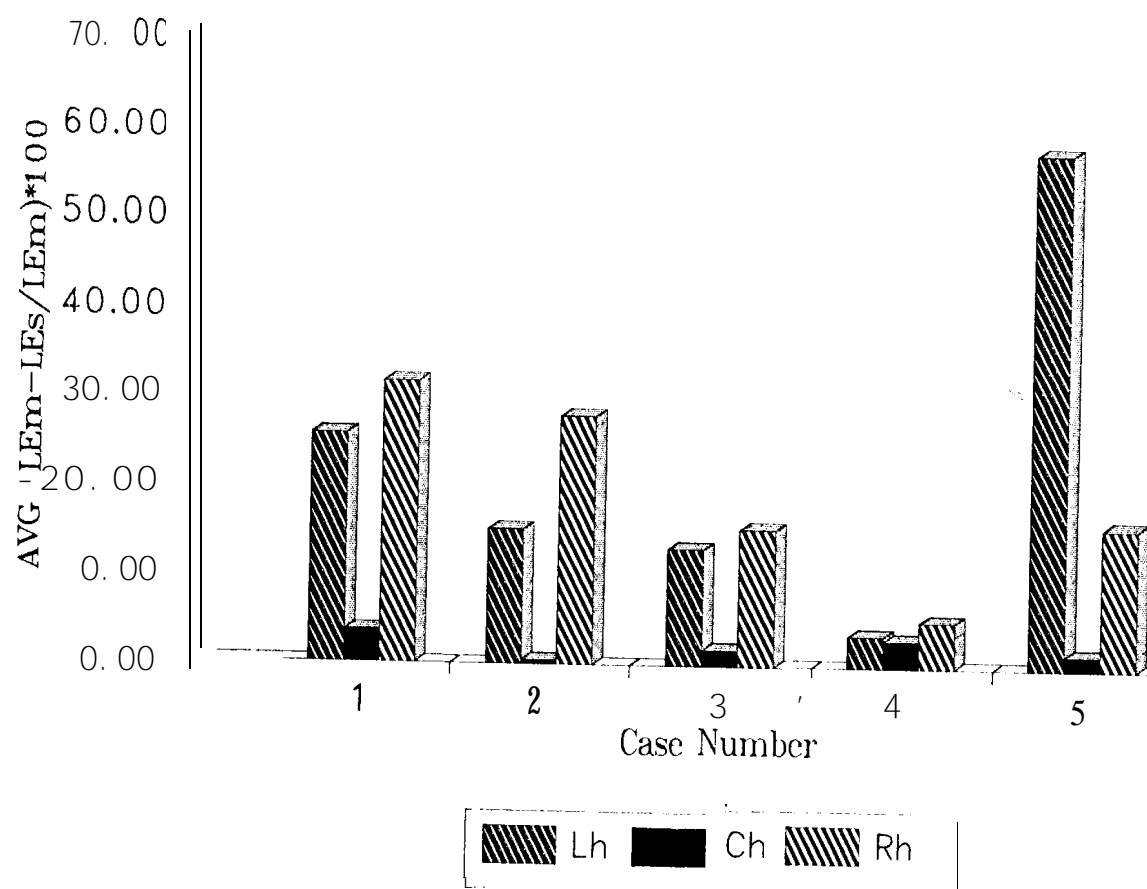


# MODELS COMPARISON Sensible Heat Flux



# MODELS COMPARISON

Latent Heat Flux



# SENSITIVITY ANALYSIS Precision Assessment

